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DISCOVERY OF A NEARBY HALO WHITE DWARF WITH PROPER MOTION $\mu = 2.55''$ YR^{-1}

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ABSTRACT

We report the discovery of PM J13420-3415, a faint (V=17) white dwarf with a very high proper motion $\mu = 2.55''$ yr^{-1}. The star was found in the southern sky extension of the SUPERBLINK proper motion survey. A red spectrum shows the classical signature of a DA white dwarf, with a weak $H\alpha$ line in absorption as the only prominent feature. The star is also found to have a large radial velocity $V_{rad} = +212 \pm 15$km s^{-1}. At the adopted distance of 18pc, the star has a very large space motion of 313 km s^{-1} relative to the Sun. An integration of the space motion shows that the star is on a nearly polar Galactic orbit, and is thus an unambiguous member of the Galactic halo. However, with an estimated effective temperature $5,000K < T_{eff} < 5,500K$, the white dwarf appears to be much younger than expected for a denizen of the halo. The apparent paradox can be explained if the white dwarf is the relatively young ($\sim$ 2Gyr) remnant of a longer-lived ($10-14$Gyr) main sequence star, in which case the object is predicted to be a low-mass white dwarf with $M \approx 0.45 M_{\odot}$.

Subject headings: astrometry — white dwarfs — solar neighborhood — Galaxy: halo — Galaxy: stellar content

1. INTRODUCTION

Halo white dwarfs are expected to be found in the Solar Neighborhood ($d < 25pc$) as faint stars with very large proper motions. While their number density is predicted to be low ($\sim 2 \times 10^{-5}$ pc^{-3}), the empirical determination of their density and luminosity function has significant implications for the formation and evolution of the Galaxy. Halo white dwarfs are a candidate for baryonic dark matter (Ibata *et al.* 2000); they can also be used to constrain the age of the galactic halo (Fontaine, Brassard, & Bergeron 2001).

Unfortunately, the current census of halo white dwarfs in the Neighborhood of the Sun is limited to a small number of candidate objects, and is probably very much incomplete at this time. A sample of only six candidate halo white dwarfs was originally assembled by Liebert, Dahn, & Monet (1989) out of the very high proper motion stars listed in the LHS catalog of Luyten (1979a). Few additional high velocity white dwarfs were identified in subsequent proper motion surveys. A pair of cool (4000K), common proper motion ($\mu = 1.9''$ yr^{-1}) white dwarfs was discovered by Scholz *et al.* (2002), but their status as halo objects remain uncertain. A group of 38 high proper motion white dwarfs were identified in a survey of the south Galactic cap (Oppenheimer *et al.* 2001), but their halo membership is under debate, as reviewed in Koester (2003) and Hansen & Liebert (2003). The main objections are based on the apparent young age of the group, more consistent with a disk population (e.g. Bergeron 1993), and about proper motion selection effects, which suggest that most or all the stars in the group are extreme members of the Galactic thick disk (e.g. Spagna *et al.* 2005).

An independent approach to finding halo white dwarfs is based on the identification of very old, ultra-cool objects from multiband photometry (Gates *et al.* 2004). It remains true, however, that any population of white dwarfs can only be reliably associated with the Galactic halo based on the kinematics of the group, which does require proper assessment of their radial velocities, distances, and proper motions.

In this Letter, we report the identification of a faint white dwarf with a very high proper motion ($\mu = 2.55''$ yr^{-1}) and large radial velocity ($V_{rad} = +212$km s^{-1}). The highly probable halo membership of this white dwarf is discussed in terms of its extreme kinematics and debated with respect to its apparently young age.

2. PROPER MOTION DISCOVERY AND PHOTOMETRY

The high proper motion star PM J13420-3415 was discovered as part of the SUPERBLINK survey for high proper motion objects in the Digitized Sky Survey (DSS), recently extended to southern declinations Lépine (2005a). A detailed description of the survey method is found in Lépine, & Shara (2005). The star was found by the SUPERBLINK software after analysis of scans of SERC-J (blue) and SERC-SR (red) photographic survey plates, separated by 16 years. A search for additional sightings of the star yielded positive identification in one SERC-I plate (also in the DSS), and in a 2MASS survey image. Figure 1 displays the discovery field at four different epochs spanning almost 25 years.

A proper motion of $2.55''$ yr^{-1} is calculated based on the position of the star on the SERC-J DSS scan, used as the first epoch, and its position recorded in the 2MASS All-Sky Catalog of Point Sources (Cutri *et al.* 2003), used as the second epoch. We derive a transformation from the DSS scan XY positions into the 2MASS J2000 coordinate system by using a set of 5 moderately bright ($13 < J < 16$) reference stars within $1.5'$ of PM J13420-3415. The XY position of PM J13420-3415 on the DSS scan was then transformed into its corresponding J2000 coordinates in the 2MASS reference frame. We calculate a proper motion of -$2.275''$ yr^{-1} in the direction of R.A., and $1.145''$ yr^{-1} in the direction of Decl., both with an estimated error of $0.012''$ yr^{-1}. Data on the star are compiled in Table 1.

Photometry is obtained from the 2MASS All-Sky Catalog and from the USNO-B1.0 catalog (Monet *et al.* 2003). In USNO-B1.0, the star matches the source 0557-0303180. Although this source is not listed in the USNO-B1.0 as having any proper motion, 0557-0303180 clearly matches the position of PM J13420-3415 at the epoch of the SERC-SR plate.

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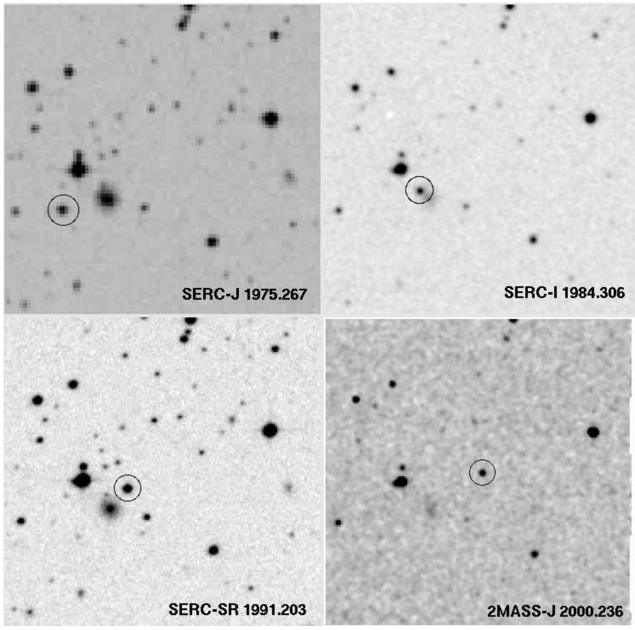

FIG. 1.— Four different sightings of the new high proper motion white dwarf PM J13420-3415 (μ=2.55″ yr^{-1}). The position of the star is marked with a circle. Upper left: SERC-J photographic survey, blue band (IIIaJ+GG395). Upper right SERC-I photographic survey, near-infrared band (IVN+RG715). Lower left: SERC-SR photographic survey, red band (IIIaF+GG395). Lower right: 2MASS infrared CCD survey (J band image shown). The epoch of each survey image is noted on the lower right. Each field is 3.15′ on the side.

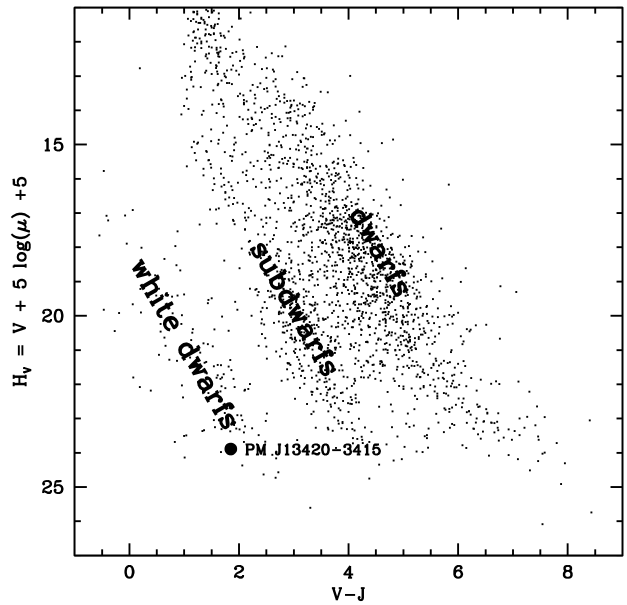

FIG. 2.— Reduced proper motion diagram, with PM J13420-3415 superposed on the distribution of $\mu > 0.5''$ yr^{-1} stars from the LSPM-north catalog. PM J13420-3415 lies well into the locus of (cool) white dwarfs.

TABLE 1
BASIC DATA FOR PM J13420-3415

Datum	Value	Units
RA (2000.0)	13 42 2.84	h:m:s
DEC (2000.0)	-34 15 19.1	d:m:s
μ_{RA}	-2.275	″ yr^{-1}
μ_{Decl}	1.145	″ yr^{-1}
V_{rad}	+212 ±15	km s^{-1}
B_J [1]	17.5 ±0.3	mag
R_F [1]	16.1 ±0.3	mag
J[2]	15.00±0.02	mag
H[2]	14.75±0.02	mag
K_s [2]	14.65±0.03	mag
Spectral Type	DA9.5	
Distance	18^{+7}_{-3}	pc
U	+62	km s^{-1}
V	-211	km s^{-1}
W	+233	km s^{-1}

[1]Photographic blue (*IIIaJ*) and red (*IIIaF*) magnitudes from USNO B-1.0 catalog.
[2]Infrared J, H, and K_s magnitudes from 2MASS All-Sky Catalog of Point Sources.

The source has a blue photographic magnitude B_J = 17.48 and a red photographic magnitude R_F = 16.12. These are consistent with a visual magnitude $V \simeq B_J - 0.46(B_J - R_F)$ = 16.85, with an uncertainty of 0.3 mag. In the 2MASS All-Sky Point Source Catalog, PM J13420-3415 is a match to the point source 2MASS J13420283-3415190, which has infrared magnitudes J=15.00, H=14.75, and K_s=14.65.

With a color index V-J=1.85, PM J13420-3415 is bluer than most faint stars with very high proper motions. Figure 2 shows the position of PM J13420-3415 in the $[H_V, V-J]$ reduced proper motion diagram. For comparison, the diagram also shows the 2,194 stars in the LSPM-north proper motion catalog (Lépine, & Shara 2005) that have $\mu > 0.5''$ yr^{-1}. With its blue color and large proper motion, PM J13420-3415 clearly falls into the locus of the white dwarfs, amidst the cooler, low-luminosity bodies.

3. SPECTROSCOPY, DISTANCE, AND KINEMATICS

Spectroscopy was performed on the night of 26 June 2005 with the 4m Mayall telescope on Kitt Peak. A spectrum of PM J13420-3415 was obtained with the RC Spectrograph equipped with the LB1A thick CCD. We used the 316 l/mm grating blazed at 7500Å, with an GG550 order blocking filter, and a slit of 1.5″ giving a spectral resolution of 1.74Åpixel^{-1}. Standard spectral reduction was performed with IRAF using the CCDPROC and SPECRED packages, including removal of telluric features. The spectrophotometric calibration is based on observations of four standards from Massey & Gronwall (1990). The target and standards were all observed with a slit angle within 15 degrees of the parallactic angle, so as to minimize slit loss due to atmospheric diffraction.

The spectrum bears the signature of a cool, hydrogen white dwarf (Figure 3). The only prominent feature is a shallow $H\alpha$ absorption line. The line is quite broad, with a full width at half maximum of 21 ± 2Å, and an equivalent width of 2.9Å. The spectral energy distribution appears rugged at the 5% level, with broad bumps and troughs: these are possibly residuals from the removal of sky lines and/or correction for telluric absorption features. The star was observed at an airmass of ≈ 2.6, and both sky lines and telluric absorption in that wavelength range were significant, with corrections susceptible to large errors.

We classify PM J13420-3415 as a hydrogen white dwarf with spectral subtype DA9.5. A blackbody fit to the spectrum best matches an effective temperature $T_{eff} = 5500K$. The

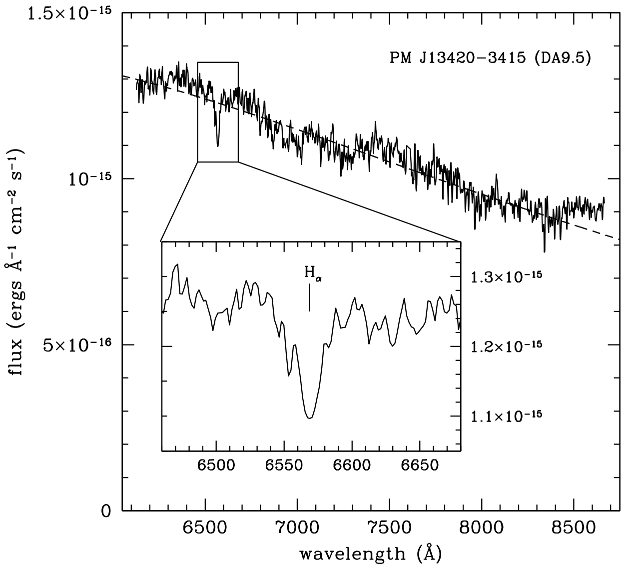

FIG. 3.— Red optical spectrum of PM J13420-3415, with a clear detection of $H\alpha$ in absorption. The spectral energy distribution matches that of a T_{eff}=5500K blackbody (dashed curve). A radial velocity of +212±15 km s^{-1} is derived from the shift in the $H\alpha$ line.

weakness of $H\alpha$ is however consistent with a slightly cooler T_{eff}. A comparison with the models and observations presented in Bergeron, Ruiz, & Leggett (1997) shows the $H\alpha$ profile to be comparable to those of DA white dwarfs with T_{eff} in the 5200K-5500K range. This temperature scale is corroborated by the photometry, based on a comparison with the atmospheric models of Bergeron, Wesemael, & Beauchamp (1995). A derivation of CIT color indices from 2MASS JHK_s magnitudes[4] yield $V-K_{CIT}$ = 2.18, $J_{CIT}-H_{CIT}$ = 0.274, and $H_{CIT}-K_{CIT}$ = 0.062 for PM J13420-3415. With all weights equal, these values are most consistent with the T_{eff} = 5000K atmospheric model ($V-K_{CIT}$=1.828, $J_{CIT}-H_{CIT}$=0.243, $H_{CIT}-K_{CIT}$=0.056). However, our V magnitude is derived from photographic data and is much more uncertain than the 2MASS infrared magnitudes. With more weight on $J_{CIT}-H_{CIT}$ and $H_{CIT}-K_{CIT}$, PM J13420-3415 is more consistent with the T_{eff} = 5500K model ($V-K_{CIT}$=1.650, $J_{CIT}-H_{CIT}$=0.260, $H_{CIT}-K_{CIT}$=0.082). It is thus reasonable at this time to adopt an intermediate value for T_{eff}, in line with a spectral subtype DA9.5.

A radial velocity of +212±15 km s^{-1} is calculated from the observed redshift in the centroid of the Hα absorption line. A fit to the line profile is made using *splot* in IRAF. The radial velocity is calibrated with a spectrum of the sdF8 standard BD +17 4708, whose radial velocity is known to ±0.5 km s^{-1} (Latham *et al.* 2002), and which we observed on the same night as PM J13420-3415 and with the same instrumental setup. The radial velocity for PM J13420-3415 includes a correction for the expected gravitational redshift. While the surface gravity of the object is not known precisely at this point, Reid (1996) finds gravitational redshifts from field white dwarfs that are 28.3km s^{-1} on average, with a dispersion of only 3.9km s^{-1}; we thus adopt a -28.3km s^{-1} correction. A error ±15 km s^{-1} is estimated from the quality of the centroid fit, the accuracy of the wavelength calibration, and the dispersion in the range of possible gravitational redshifts.

From the measured proper motion and radial velocity, the full kinematics of PM J13420-3415 can be determined based on an estimate of the distance. There exists several calibrations for absolute magnitudes as a function of either color or T_{eff}. The relationship defined by (Oppenheimer *et al.* 2001) uses photographic magnitudes B_J and R_F as follows: $M_{B_J} = 12.73+2.58(B_J-R_F)$. Under this calibration, PM J13420-3415 has an absolute magnitude M_{B_J} = 16.24, and resides at a distance d=17.7pc. A calibration of the $[M_V, V-J]$ relationship for white dwarfs with known trigonometric parallaxes (Lépine 2005a) suggests M_V = 15.5, which would be consistent with a distance d=18.6pc. The atmospheric models of (Bergeron, Wesemael, & Beauchamp 1995) suggest M_V = 14.62 for T_{eff} = 5500 hydrogen white dwarfs, and M_V = 15.11 for T_{eff} = 5000. An intermediate value would place the star at a distance of d=24.9pc. The latter distance scale would translate into a huge transverse velocity V_T = 301km s^{-1}. A more conservative distance scale $d \approx 18pc$, consistent with the two photometric distance estimates above, would yield a more modest V_T = 216km s^{-1}.

Using the more conservative distance range, we calculate the UVW components of the velocity, where U is the velocity in the direction of the Galactic center, V is in the direction of Galactic rotation, and W is towards the north Galactic pole. We find U = +57km s^{-1}, V = −207km s^{-1}, and W = +220km s^{-1}. These correspond to a total space motion of 307 km s^{-1} relative to the Sun. At the larger distance scale of 25pc, the total space motion would be 357 km s^{-1}. Note that a more conservative distance estimate of 15pc still yields a total space motion of 287 km s^{-1}, largely because of the high value of V_{rad}.

From the adopted UVW velocity components, we integrate the Galactic orbital motion using the Galactic mass model of Dauphole & Colin (1995), which includes separate terms for the bulge, disk, and halo. We use a Runge-Kutta fourth order integrator in time steps of 10^3 yr. Figure 4 shows 800 Myr integrations (for both the 18pc and 25pc distance estimates) of the orbit of the star plotted in the [R,z] plane, where R is the galactocentric distance in cylindrical coordinates, and z is the distance from the plane. In both cases (and at all intermediate distance ranges), the star is found to evolve on a nearly circumpolar orbit, overwhelmingly consistent with a halo membership.

4. DISCUSSION AND CONCLUSIONS

PM J13420-3415 largely owes its halo white dwarf status to its large component of velocity perpendicular to the Galactic plane ($W >$ 220km s^{-1}). This should be contrasted to the stars in the Oppenheimer *et al.* (2001) sample, which have $W <$100km s^{-1} (Salim *et al.* 2004). Incidentally, what distinguishes PM J13420-3415 from the Oppenheimer *et al.* (2001) white dwarfs is that it was discovered in a relatively low Galactic latitude field (b = +27), and its W is largely reflected in its large proper motion. In contrast, the Oppenheimer *et al.* (2001) white dwarfs were found near the south galactic cap, and a determination of their W velocity is entirely dependent on radial velocity measurements (which cannot be obtained for many of them since their spectrum shows no atomic line). It is clear that much would be gained from a survey of high proper white dwarfs at low Galactic latitudes. Proper motion selection would favor stars with large components of W, and

[4] See the 2MASS documentation at http://www.ipac.caltech.edu/2mass/

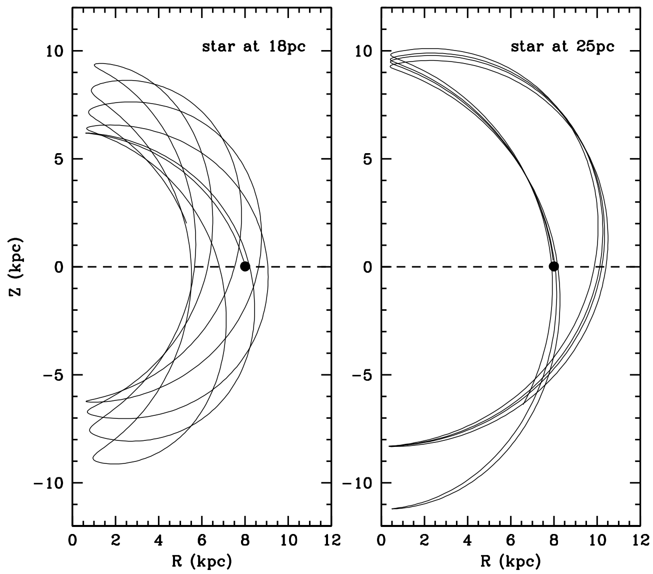

FIG. 4.— Integrated Galactic orbital motion of PM J13420-3415, based on its estimated local kinematics (UVW velocity components). The orbit is displayed in the $[R,Z]$ plane, where R is the galactocentric distance and Z the distance from the midplane. The initial UVW are dependent on the estimated distance of the star from the Sun: two solutions and given for d=18pc (left), and d=25pc (right). In both cases (and for all $18pc < d < 25pc$), the star evolves on a nearly polar orbit, and is thus clearly a denizen of the Galactic halo. Whether the star or its progenitor actually originated in the halo remains an open question.

determination of halo membership would not be as critically dependent on the determination of radial velocities. The identification of a large sample of white dwarfs on near polar orbits could lift much of the confusion that now exists between the thick disk and halo populations.

But while PM J13420-3415 has kinematics so clearly consistent with a halo membership, its spectral energy distribution raises questions about the origin its progenitor. One would expect a *bona fide* halo white dwarf to be old, which generally means a much cooler T_{eff} than exhibited by PM J13420-3415. The luminosity function of halo white dwarfs peaks at much fainter absolute magnitudes (Isern *et al.* 2003), with a 10Gyr population peaking at $M_V \simeq 16.5$, and a 14Gyr population peaking at $M_V \simeq 19$. With $M_V \approx 15$, PM J13420-3415 does not stand out as a typical remnant from early generations of star.

It has been shown that relatively young, high-velocity white dwarfs could originate in the thin disc, from which they can be ejected as companions of stars undergoing catastrophic disruption. A Type Ia supernova channel has been investigated by (Hansen 2003). However, the resulting population of ejected white dwarfs is expected to have very few objects with transverse velocities in excess of 200 km s^{-1}, which would make PM J13420-3415 an exceptional case. Likewise, most white dwarfs ejected following a Type II supernova events would have motions generally consistent with a bloated thick disc (Davies, King, & Ritter 2002).

Alternatively, PM J13420-3415 could have been accreted into the Galaxy in a merger event. The polar orbit displayed by PM J13420-3415 would, for example, be consistent with the star having been accreted from the Saggitarius dwarf Galaxy (Johnston *et al.* 1999). Should this be the case, PM J13420-3415 could be associated with a local streamer. This hypothesis would be corroborated if a whole group of stars were to be found in the Solar Neighborhood with UVW velocities similar to PM J13420-3415.

It must however be pointed out that a $T_{eff} \approx 5500$K white dwarf does not preclude an old progenitor. PM J13420-3415 could be the remnant of a moderately massive, 10-14Gyr old star that turned into a white dwarf only $\sim$2Gyr ago. In that case, however, models predict that the white dwarf should have a mass between $0.45 M_{\odot}$ and $0.50 M_{\odot}$ Fontaine, Brassard, & Bergeron (2001). This could be tested through accurate parallax measurements, which would provide a direct determination of the absolute magnitude of PM J13420-3415, and hence its current mass[5]. Indeed, mass determination now appears to be critical in determining the true origin of white dwarfs with halo-like kinematics (Bergeron *et al.* 2005). A more precise distance combined with an accurate estimate of the mass of PM J13420-3415 will thus be the key in determining the true origin of the star. The results may have significant implications about the white dwarf population in the Galactic halo.

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[5] Hypothetically, a massive white dwarf could also be compatible with old (MS+WD) age if it is the product of a merger of two low-mass degenerates; thanks to the referee (S. Vennes) for pointing this out.

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